Workforce Demographics and Technology Adoption

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Introduction and Motivation

Broad Research Question

What is the effect of population aging on growth?

- Wide-spread population aging has two effects on the labor force:
  1. Scale Effect: size of labor force ↓;
  2. Composition Effect: more old workers, less young ones.
- Standard View
  - Scale effect reduces output, productivity, and firm creation.
    Hopenhayn et al. [2022],Maestas et al. [2023],Aksoy et al. [2019],Bloom et al. [2020],Karahan et al. [2024]
  - Higher Tech Adoption can mitigate the Scale effect. *Acemoglu and Restrepo [2022]*
- **Our Paper**: What if young workers are better at operating new technologies?
  - Composition effect puts a constraint on Tech adoption.

This Talk

Today:

- **Theory:**
  - Firm-dynamics model with endogenous technology adoption.
  - Technologies are a bundle of "new skills" and production skills.
    - More recent technologies are more productive and more intensive in new skills.
  - Young workers have an effective-cost advantage over old workers in new skills.

- **Empirics:**
  - Matched employer–employee data and technology adoption survey from Portugal.

Future:

- **Quantitative Evaluation:**
  - Model Extensions and calibration.

Outline

Demographics

- Time is discrete: $t = 1, 2, 3, \ldots$
- **Demographic structure**:
  - Measure $\mathcal{L}_t$ of households $\implies$ share μ_t of young, $1 - \mu_t$ of old.
  - Stochastic aging: probability δ_y of young becoming old, probability δ_o of old dying.
- Population evolves deterministically (constant for Today)

$$\mathcal{L}_{y,t} = (1 - \delta_y)\mathcal{L}_{y,t-1} + \underbrace{\delta_o \mathcal{L}_{o,t-1}}_{\text{Newborns}}$$

$$\mathcal{L}_{o,t} = \delta_y \mathcal{L}_{y,t-1} + (1 - \delta_o)\mathcal{L}_{o,t-1}$$

- Households inelastically supply one unit of labor and are hand-to-mouth.

Production Technologies

- Exogenous technological progress:
  - At any t, two available technologies: frontier ($\tau = 0$) and laggard ($\tau = 1$).
  - In $t+1$: $\tau_{t+1} = 0$ enters, $\tau_t = 0 \to 1$, $\tau_t = 1$ exits.
- Two types of labor inputs needed for production
  - New Skills (N), Production Skills (P).
- The production function of technology τ is

$$y_{\tau,t} = \underbrace{z_t \boldsymbol{\lambda}^{-\tau}}_{\text{TFP}} \underbrace{\left[\boldsymbol{\alpha}_\tau L_{N,t}^\rho + (1-\boldsymbol{\alpha}_\tau) L_{P,t}^\rho\right]^{\frac{\eta}{\rho}}}_{\text{Labor Composite}}, \quad \eta < 1,\ \lambda > 1$$

$$\text{s.t.} \quad L_{N,t} = \boldsymbol{\gamma}^{\boldsymbol{N}} l_{y,t}^N + l_{o,t}^N, \qquad L_{P,t} = l_{y,t}^P + \gamma^P l_{o,t}^P$$

- Young workers have a **comparative advantage** in new skills ($\gamma > 1$).
- Technologies are a fixed-bundle of:
  - **Productivity** ($\lambda^{-\tau}$) $\to$ Lower for laggard tech.
  - **Intensity in New Skills** (α_τ) $\to$ Higher for frontier tech.

Firms

- Individual state variables: $s \equiv (z, l_o^-, \tau^-)$
  - Idiosyncratic productivity shock $z' \sim F_{z'|z}$, $z \in \{z_l, z_h\}$.
  - Stock of old workers l_o^-, subject to adjustment costs.
  - Previous technology τ^-, frontier ($\tau^- = 0$) or laggard ($\tau^- = 1$).
- In each period, firm chooses the following:
  1. If $\tau^- = 0$: adopt new technology (A, $\tau = 0$), keep technology (K, $\tau = 1$) or exit ($\emptyset$).
  2. If $\tau^- = 1$: adopt new technology (A, $\tau = 0$) or exit ($\emptyset$).
  3. Labor demand $\left(l_y^N, l_o^N, l_y^P, l_o^P\right)$, where
     - Stock of old workers changes subject to convex adjustment costs $\Delta(l_o, l_o^-)$.
- Firms pay
  - Adoption cost φ_A, if it chooses to adopt.
  - Operating cost φ_P.
- Exit is costless.
- Large mass of potential entrants $\mathcal{M}$: draw random entry cost $f_e \sim \mathcal{U}[0, \bar{f}_e]$.

Problem of the Adopting Firm (A)

Trade-off: higher productivity $(1 > \lambda^{-1})$ vs higher intensity in new skills $(\alpha_0 > \alpha_1)$.

$$V(z, l_o^-, \tau^-; \tau = 0) = \max_{l_y^N, l_o^N, l_y^P, l_o^P \geq 0} \Big\{ \underbrace{z\Big[\alpha_0 L_N^\rho + (1-\alpha_0) L_P^\rho\Big]^{\frac{\eta}{\rho}} - w_y(l_y^N + l_y^P) - w_o(l_o^N + l_o^P)}_{\text{Operating Profits}} -$$

$$\underbrace{\psi |l_o^P + l_o^N - l_o^-|^\xi}_{\text{Labor Adjustment Cost } \Delta(l_o, l_o^-)} - \underbrace{\varphi_A}_{\text{Adoption Cost}} - \underbrace{\varphi_P}_{\text{Operating Cost}} +$$

$$\underbrace{\frac{1}{R}\mathbb{E}_{z'|z}\Big[\hat{V}(z', l_o, 0)\Big]}_{\text{Continuation Value}} \Big\}$$

$$\text{sub. to} \quad L_N = \gamma l_y^N + l_o^N, \quad L_o = l_y^P + l_o^P$$

$$l_o = \delta_y(l_y^N + l_y^P) + (1-\delta_o)(l_o^N + l_o^P)$$

Problem of the Non-adopting Firm (K)

$$V(z, l_o^-, \tau^-; \tau = 1) = \max_{l_y^N, l_o^N, l_y^P, l_o^P \geq 0} \Bigg\{ \underbrace{z\lambda^{-1}\left[\alpha_1 L_N^\rho + (1-\alpha_1) L_P^\rho\right]^{\frac{\eta}{\rho}} - w_y(l_y^N + l_y^P) - w_o(l_o^N + l_o^P)}_{\text{Operating Profits}} -$$

$$\underbrace{\psi|l_o^P + l_o^N - l_o^-|^\xi}_{\text{Labor Adjustment Cost } \Delta(l_o, l_o^-)} - \underbrace{\varphi_P}_{\text{Operating Cost}} +$$

$$\underbrace{\frac{1}{R}\mathbb{E}_{z'|z}\left[\hat{V}(z', l_o,, 1)\right]}_{\text{Continuation Value}} \Bigg\}$$

sub. to $\quad L_N = \gamma l_y^N + l_o^N, \quad L_o = l_y^P + l_o^P$

$$l_o = \delta_y(l_y^N + l_y^P) + (1-\delta_o)(l_o^N + l_o^P)$$

Problem of the firm

- In each period the firm chooses the option that maximizes its value.
  - If previously frontier ($\tau^- = 0$)

$$\hat{V}(z, l_o^-, 0) = \max\Big\{\underbrace{V(z_t, l_o^-, 0; \tau = 0)}_{\text{Adopt } (A)}, \underbrace{V_t(z, l_o^-, 0; \tau = 1)}_{\text{Keep } (K)}, \underbrace{0}_{\text{Shut Down } (\emptyset)}\Big\}$$

  - If previously laggard ($\tau^- = 1$)

$$\hat{V}(z, l_o^-, 1) = \max\Big\{\underbrace{V_t(z_t, l_o^-, 1; \tau = 0)}_{\text{Adopt } (A)}, \underbrace{0}_{\text{Shut Down } (\emptyset)}\Big\}$$

Equilibrium

A stationary equilibrium consists in a value function $\hat{V}(s)$, policy functions for labor $l_y^N(s), l_y^P(s), l_o^N(s), l_o^P(s)$, adoption rules $\tau(s)$, a distribution $\Lambda(s)$, cohort-specific wages $\{w^y, w^o\}$, and a mass of entrants m_e such that:

- ***Optimality***.
- ***Labor Market Clearing***: labor markets segregated by age (not by task)

$$\mathcal{L}_y = \int \left[l_y^N(s;S) + l_y^P(s;S) \right] d\Lambda(s), \qquad \mathcal{L}_o = \int \left[l_o^N(s;S) + l_o^P(s;S) \right] d\Lambda(s)$$

- ***Stationarity Distribution***.
- ***Free-entry***: $\quad m_e = \frac{\mathbb{E} V^e}{\bar{f}_e}$

Future Extensions

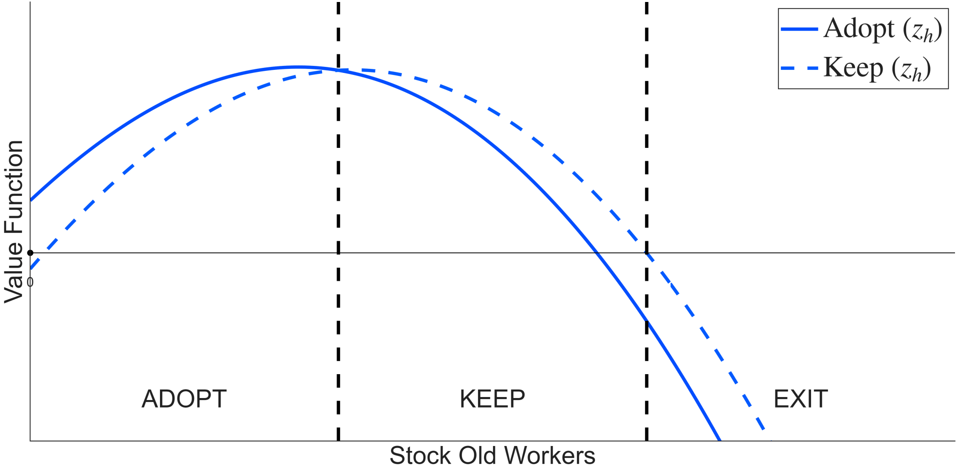
- **Today**: numerical example to illustrate the model's main prediction qualitatively.
- **Future extensions** for quantitative purposes:
  - Full growth model $\implies$ endogenous set of vintages operated in equilibrium ($|\tau|$).
    Chari and Hopenhayn [1991]
  - Characterize the BGP for given workforce age composition.
  - Study impact of population aging $\implies$ transition with declining share of young (μ).

Full Model

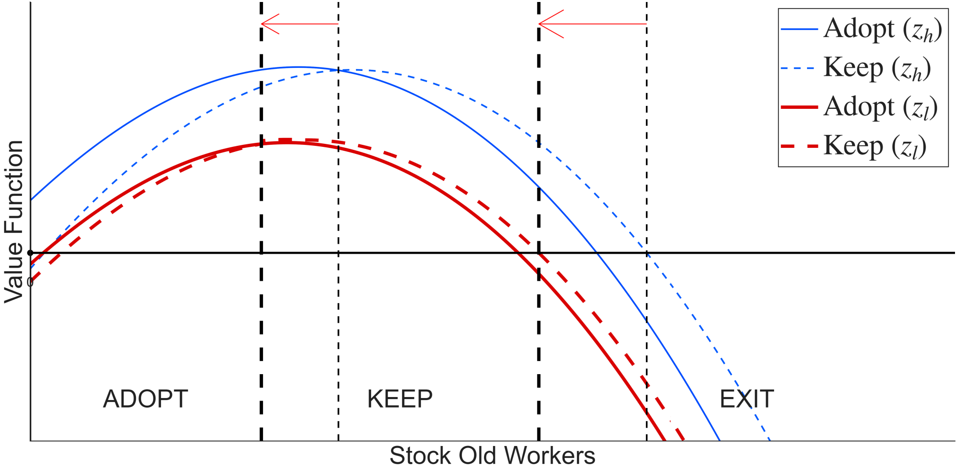
Outline

1. The Model
2. Stationary Equilibrium
3. Empirical Analysis
4. Conclusions

Prediction 1: Adoption decreases in the stock of old workers

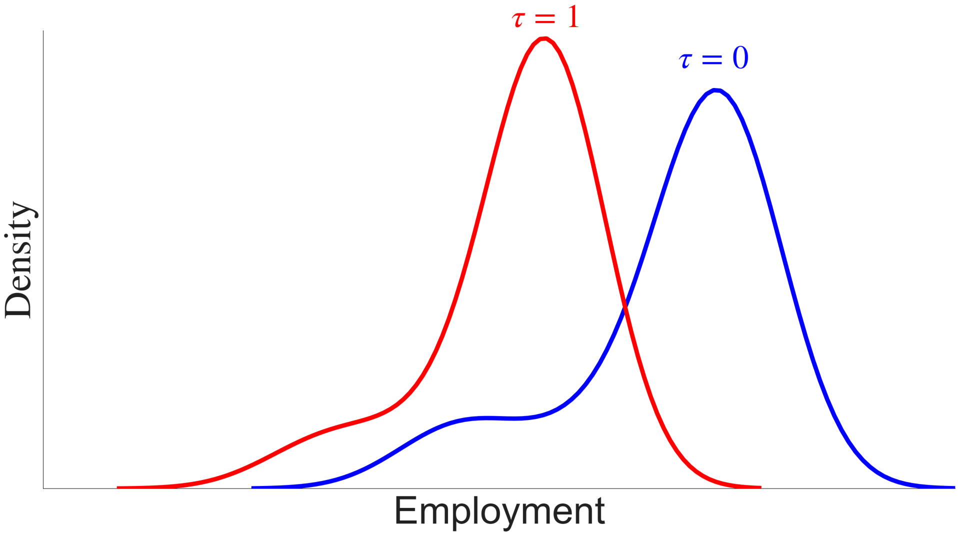


Prediction 2: Adoption increases with productivity



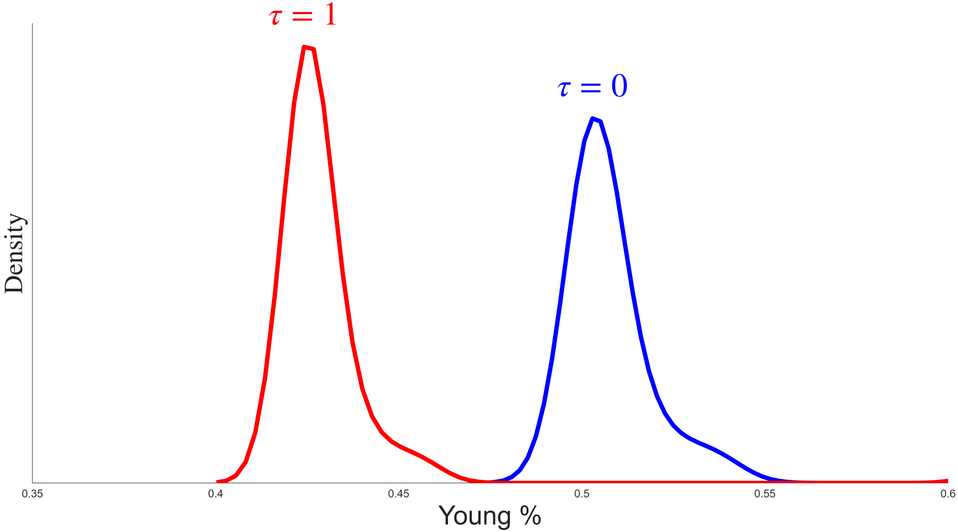
Prediction 3: Adopting firms employ more workers

- Frontier firms ($\tau = 0$) has a larger optimal scale due to productivity boost ($\lambda^{-\tau}$).



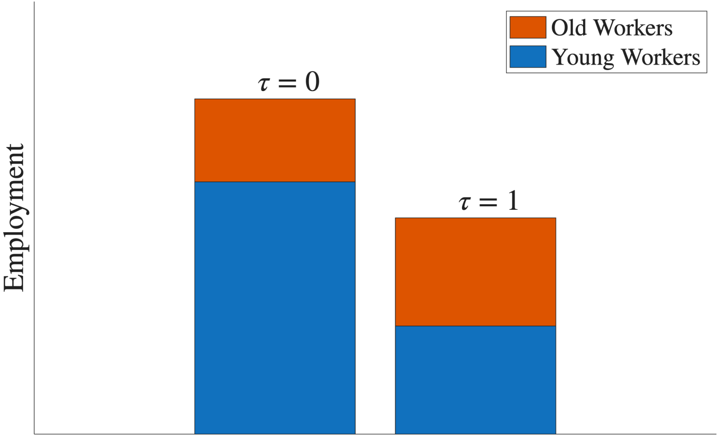
Prediction 4: Adopting firms are more young-intensive

- Intensive in new-skills ($\alpha_0 > \alpha_1$) + young have a comparative advantage.



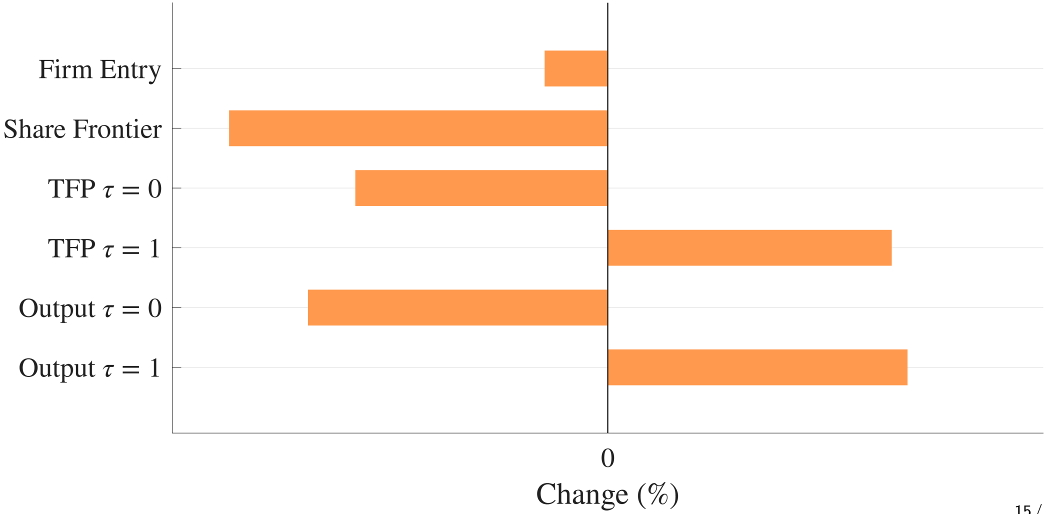
Prediction 5: Adopting firms expand employment by hiring young

- Compare optimal hiring of firms ($\tau^- = 0$): ADOPT ($\tau = 0$) vs KEEP ($\tau = 1$).



Comparative Statics: Change Workforce Composition

- Example: Change share of young from 50% to 45%.



Summary of the Model Predictions

- **Main predictions**:
  1. Adopting firms are more productive, employ more workers, and are more young-intensive.
  2. Adopting firm expand their relative employment by hiring young workers.
- **Next**: Test predictions using firm microdata (today Portugal, future Germany).

Outline

Data

- UTICE (2007-2024): Annual survey on tech-adoption.
  - Technologies: Cloud Computing, Big Data, RFID, ERP, AI, IoT
  - We build a panel of events of Tech Adoption at the firm level.
- Quadros de Pessoal (2004-2023): matched employer-employee data
  - workers job history, wages, occupation, demographics of workers.
- SCIE (2004-2023): balance sheet data
  - Sales, value added, wage bill.

Exercise 1: Test Cross-Sectional Predictions

Model's Predictions

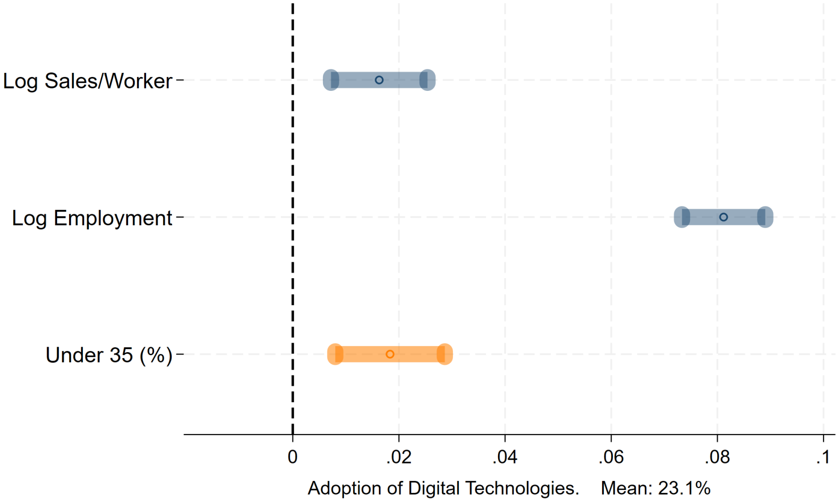
- Adoption is positively correlated with
  1. Firm's Productivity
  2. Firm's Employment
  3. Share of Young Workers

Empirical Specification

$$\mathbb{I}(\text{Adopt})_t = \alpha + \beta_1 \text{Log Sales/W}_t + \beta_2 \text{Log Employment}_t + \beta_3 \text{Under 35 (\%)}_t + \Gamma X_t + \varepsilon_t$$

- Controls: Sector×Year, Region×Year, Firm Age, College (%), Payroll.

Exercise 1: Test Cross-Sectional Predictions



Exercise 2: Test Dynamic Predictions

Model's Predictions

- After an event of Tech Adoption
  1. Firm's Employment increases.
  2. Workforce becomes younger.

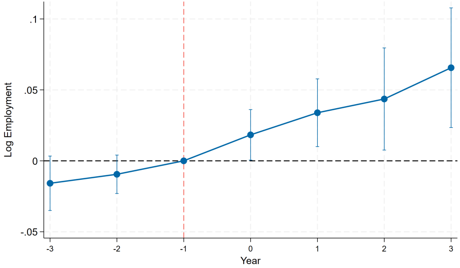
Empirical Strategy→ Events of Tech Adoption at firm level.

- *matching cells*: 3-digits sector, employment bin at $t-1$ and $t-3$, firm age bins.
- Empirical Specification:

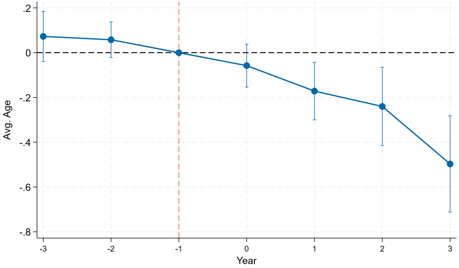
$$y_{ft} = \alpha_f + \gamma_t + \sum_k \theta_k D_{ft}^k + \sum_k \beta_k (D_{ft}^k \times \text{Tech Adoption}_f) + \varepsilon_{ft},$$

  - y_{ft} outcome of interest for firm f in year t.
  - $D_{ft}^k \equiv \mathbf{1}\{t_f = t + k\}$ event-study indicators with t_f year of technology adoption.
  - $\text{Tech Adoption}_f = 1$ if firm f has adopted a digital technology.
  - α_f and γ_t firm and year fixed effects.

Exercise 2: Test Dynamic Predictions

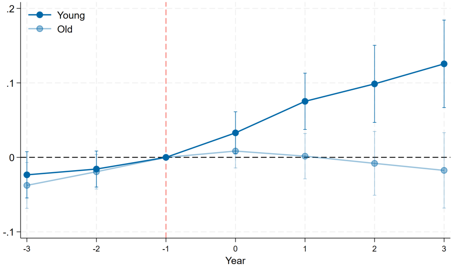


(a) Employment

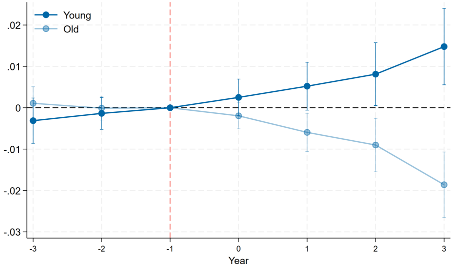


(b) Avg Age

Exercise 2: Employment change by Age Groups



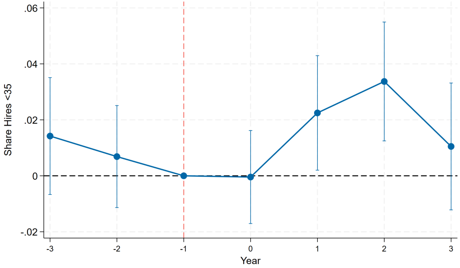
(a) Log Employment



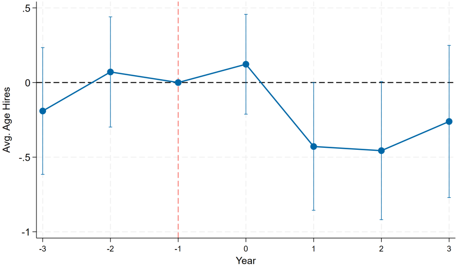
(b) Employment Share

Age-Education Occupation Decomposition

Exercise 2: Composition of New Hires



(a) Under 35 (%)



(b) Avg Age

Outline

1. The Model
2. Stationary Equilibrium
3. Empirical Analysis
4. Conclusions

Conclusions

Today

- Firm dynamics model with endogenous technology adoption.
- Young workers are better in new tasks needed for frontier technologies.
- The adoption of technologies is endogenous to the age workforce composition.
- Derive qualitative predictions that we test using data from Portugal.

Future

References I

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Full Model - Production Technologies

- Exogenous technological progress: a new vintage appears every period.
  - At t, ladder of available technologies $\{A_i\}_{i=1,\dots,t}$, where $A_t = \lambda^t A_0$.
- Two types of labor inputs needed for production
  - New Skills (N), Production Skills (P).
  - Young workers have a comparative advantage in new skills ($\gamma > 1$).
- Two technologies differ in:
  - Productivity (λ^i), with $\lambda > 1$.
  - Importance of new skills, higher for frontier technology ($\frac{\partial \alpha(i)}{\partial i} > 0$).
- The production function of technology τ is

$$y_{i,t} = z_t \boldsymbol{\lambda}^i \left[\boldsymbol{\alpha_i} L_{N,t}^{\rho} + (1 - \boldsymbol{\alpha}_i) L_{P,t}^{\rho} \right]^{\frac{\eta}{\rho}}, \quad \eta < 1$$

$$\text{s.t.} \quad L_{N,t} = \boldsymbol{\gamma} l_{y,t}^{N} + l_{o,t}^{N}, \qquad L_{P,t} = l_{y,t}^{P} + l_{o,t}^{P}$$

Full Model - Firm's Problem

- Individual state variables: $s \equiv (z, l_o^-, A_i^-)$
  - Idiosyncratic productivity shock $z' \sim F_{z'|z}$, $z \in [\underline{z}, \overline{z}]$.
  - Stock of old workers l_o^-, subject to adjustment costs.
  - Previous vintage A_i^-, where $i^- \in \{0, \dots, t-1\}$
- In each period, firms choose the following:
  1. Adopt the frontier technology $(A,\ i = t)$, keep vintage $(K,\ i = i^-)$, or exit $(\emptyset)$.
  2. Labor demand $\left(l_y^N, l_o^N, l_y^P, l_o^P\right)$, where
     - Stock of old workers changes subject to convex adjustment costs $\Delta(l_o, l_o^-)$.
- Firm pays
  - Adoption cost φ_A, if it chooses to adopt.
  - Operating cost φ_P.
- Exit is costless.
- Large mass of potential entrants $\mathcal{M}$ draw cost $f \sim \mathcal{U}[0, \bar{f}_e]$.

Full Model - Problem of the Adopting Firm (A)

$$V_t(z, l_o^-, A_i^-; A_t) = \max_{l_y^N, l_o^N, l_y^P, l_o^P \geq 0} \Big\{ zA_t \left[\alpha_0 L_N^\rho + (1-\alpha_0) L_P^\rho \right]^{\frac{\eta}{\rho}} - w_y(l_y^N + l_y^P) - w_o(l_o^N + l_o^P) - \underbrace{\psi |l_o^P + l_o^N - l_{o,t}^-|^\xi}_{\text{Labor Adjustment Cost } \Delta(l_o, l_o^-)} - \underbrace{\varphi_A}_{\text{Adoption Cost}} - \underbrace{\varphi_P}_{\text{Operating Cost}} + \frac{1}{R} \mathbb{E}_{z'|z} \left[\hat{V}_{t+1}(z', l_o, A_t) \right] \Big\}$$

$$\text{sub. to} \quad L_N = \gamma_y^N l_y^N + \gamma_o^N l_o^N, \quad L_o = \gamma_y^P l_y^P + \gamma_o^P l_o^P$$

$$l_o = \delta_y (l_y^N + l_y^P) + (1-\delta_y)(l_o^N + l_o^P)$$

Full Model - Problem of the Non-adopting Firm (K)

$$V_t(z, l_o^-, A_i^-; A_i) = \max_{l_y^N, l_o^N, l_y^P, l_o^P \geq 0} \Big\{ z A_i \Big[\alpha_i L_N^\rho + (1-\alpha_i) L_P^\rho \Big]^{\frac{\eta}{\rho}} - w_y (l_y^N + l_y^P) - w_o (l_o^N + l_o^P) -$$

$$\underbrace{\psi |l_o^P + l_o^N - l_{o,t}^-|^\xi}_{\text{Labor Adjustment Cost } \Delta(l_o, l_o^-)} - \underbrace{\varphi_P}_{\text{Operating Cost}} +$$

$$\frac{1}{R} \mathbb{E}_{z'|z} \Big[\hat{V}_{t+1}(z', l_o, A_i) \Big] \Big\}$$

$$\text{sub. to} \quad L_N = \gamma_y^N l_y^N + \gamma_o^N l_o^N, \quad L_o = \gamma_y^P l_y^P + \gamma_o^P l_o^P$$

$$l_o = \delta_y (l_y^N + l_y^P) + (1 - \delta_y)(l_o^N + l_o^P)$$

Full Model - Problem of the firm

- In each period the firm chooses the option that maximizes its value.

$$\hat{V}_t(z, l_o^-, A_i^-) = \max\Big\{\underbrace{V_t(z_t, l_o^-, A_i^-; A_t)}_{\text{Adopt } (A)}, \underbrace{V_t(z, l_o^-, A_i^-; A_i)}_{\text{Keep } (K)}, \underbrace{0}_{\text{Shut Down } (\emptyset)}\Big\}$$

Full Model - Balanced Growth Path

- Intuition: Stationary Equilibrium after the right normalization.
- Assumption 2. The fixed costs grow proportionally with the frontier:

$$\varphi_{A,t} = \tilde{\varphi}_A A_t, \quad \varphi_{P,t} = \tilde{\varphi}_P A_t, \quad \kappa_t = \tilde{\kappa} A_t, \quad \psi_t = \tilde{\psi} A_t$$

- Existence of a BGP requires $w_{y,t} = \tilde{w}_y A_t, \quad w_{o,t} = \tilde{w}_o A_t$.

Full Model - Homogeneity of Value Functions

- Taking the ratio $\frac{V_t(z_t, l_{o,t}^{-}, A_i)}{A_t}$ yields

$$\tilde{V}_t(z, l_{o,t}^{-}, \tau^{-}; \tau) = \max_{l_y^N, l_o^N, l_y^P, l_o^P \geq 0} \Big\{ z_t \lambda^{-\tau} \left[\alpha_\tau L_N^\rho + (1-\alpha_\tau) L_P^\rho \right]^{\frac{\eta}{\rho}} - \tilde{w}_y (l_y^N + l_y^P) - \tilde{w}_o (l_o^N + l_o^P)$$

$$- \tilde{\psi} | l_o^P + l_o^N - l_{o,t}^{-} |^\xi - \tilde{\varphi}_P + \frac{1}{R_t} \mathbb{E}_{z_{t+1}|z_t} \left[\hat{\tilde{V}}_{t+1}(z_{t+1}, l_{o,t+1}^{-}, \tau) \right] \Big\}$$

$$\text{sub. to} \quad L_N = \gamma_y^N l_y^N + \gamma_o^N l_o^N, \quad L_o = \gamma_y^P l_y^P + \gamma_o^P l_o^P$$

$$l_{o,t+1}^{-} = \delta_y (l_y^N + l_y^P) + (1-\delta_y)(l_o^N + l_o^P)$$

Full Model - Joint Distribution (1/2)

- The individual state variables are

$$s = \left(z, l^{-}_{o,t}, \tau^{-}\right) \in \mathbb{R}^{+} \times \mathbb{R}^{+} \times \mathbb{N}$$

- The policy functions are the following
  - Young Workers: $l^{N}_{y,t}(s),\ l^{P}_{y,t}(s)$
  - Old Workers: $l^{N}_{o,t}(s),\ l^{P}_{o,t}(s)$
  - Vintage: $\tau_t(s)$
  - Continue Operating: $d_t(s) \in \{0,1\}$

- Define a Borel set over the state space as

$$\mathcal{B} \equiv \mathcal{Z} \times \mathcal{O} \times \mathcal{T} \in \mathbb{R}^{+} \times \mathbb{R}^{+} \times \mathbb{N}$$

Full Model - Joint Distribution (2/2)

- For each Borel set $\mathcal{B}$, define the following set:

$$\mathcal{C}(\mathcal{B}) \equiv \Big\{ s \mid \underbrace{\delta_y \Big[I_y^N(s;S) + I_y^P(s;S) \Big] + (1-\delta_o) \Big[I_o^N(s;S) + I_o^P(s;S) \Big]}_{\text{Future} \quad I_o^-} \in \mathcal{O},$$

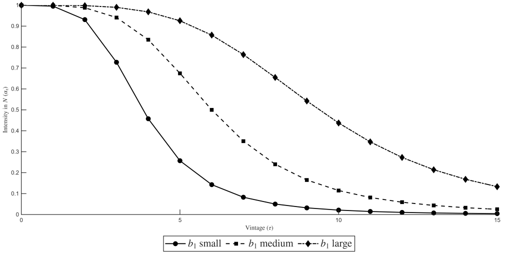
$$\underbrace{\tau(s;S)}_{\text{Future} \quad \tau^-} \in \mathcal{T}, \quad \underbrace{d(s;S) = 1}_{\text{Continue Operation}} \Big\}$$

- The law of motion of the joint distribution can be expressed as

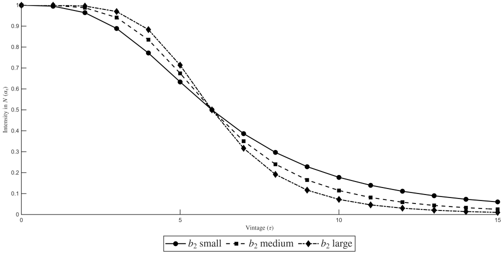
$$\Lambda'(\mathcal{B}) = \underbrace{\int_{\mathcal{C}(\mathcal{B})} \int_{z' \in \mathcal{Z}} dF(z'|z) d\Lambda(s;S)}_{\text{Firms that keep operating}} + \underbrace{\mathcal{M}\mathbb{I}\{0 \in \mathcal{O}\} \int_{\mathcal{T}} \int_{z' \in \mathcal{Z}} dF(z') d\Lambda(\tau^-)}_{\text{New Entrants}}$$

Back

Intensity in New Skills



(c) Vary b_1



(d) Vary b_2

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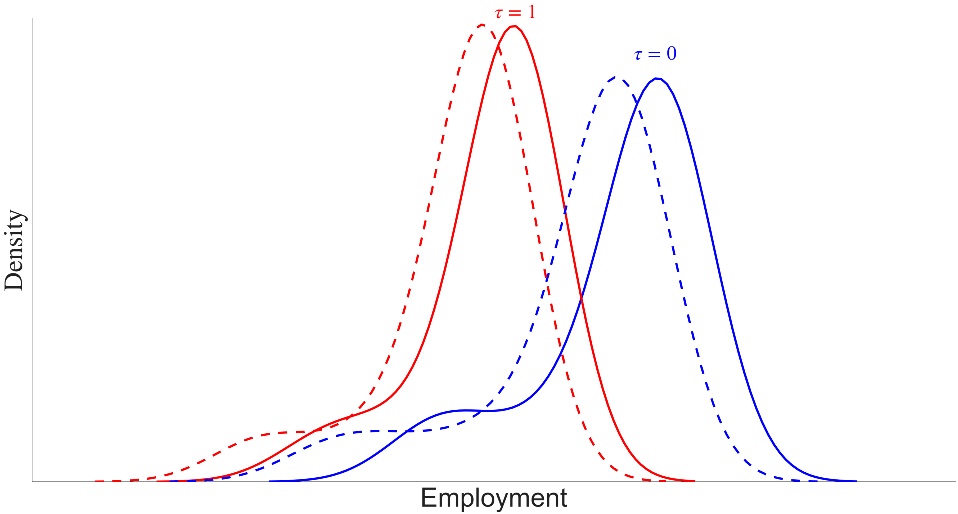
Distribution of Employment



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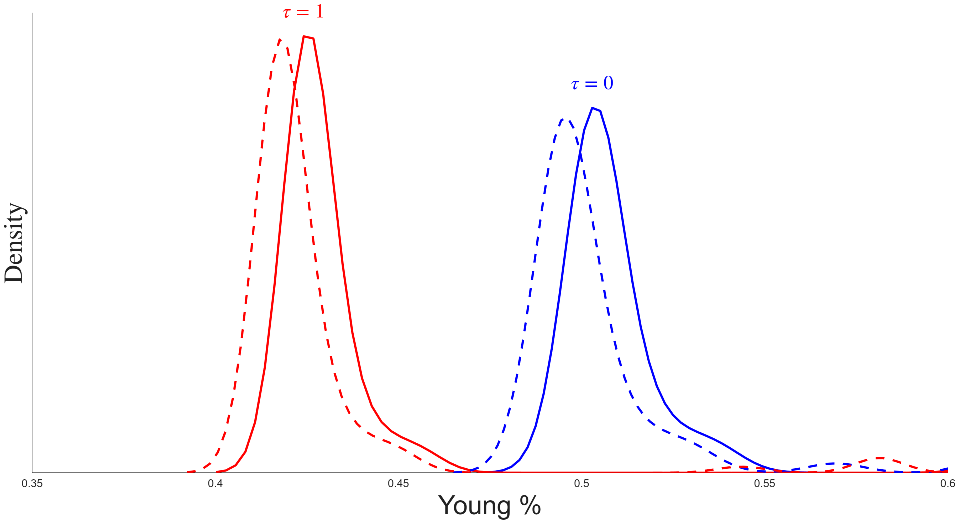
Distribution of Young Share



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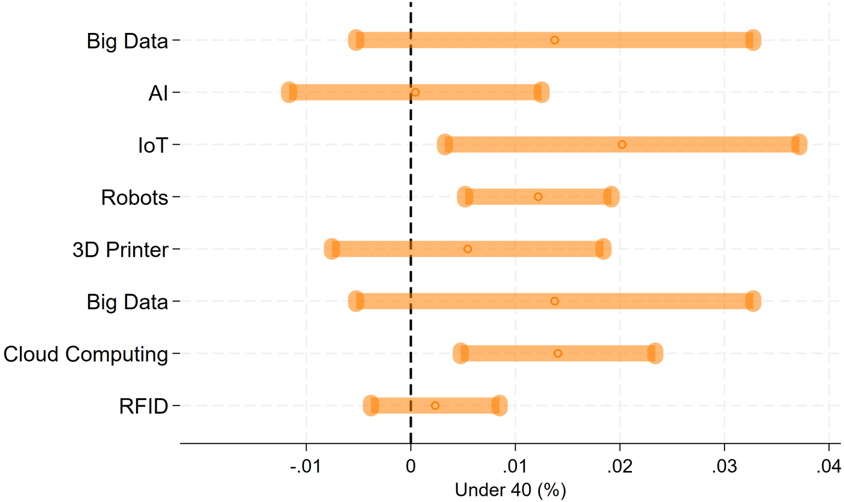
Adoption of Technologies in the Cross Section



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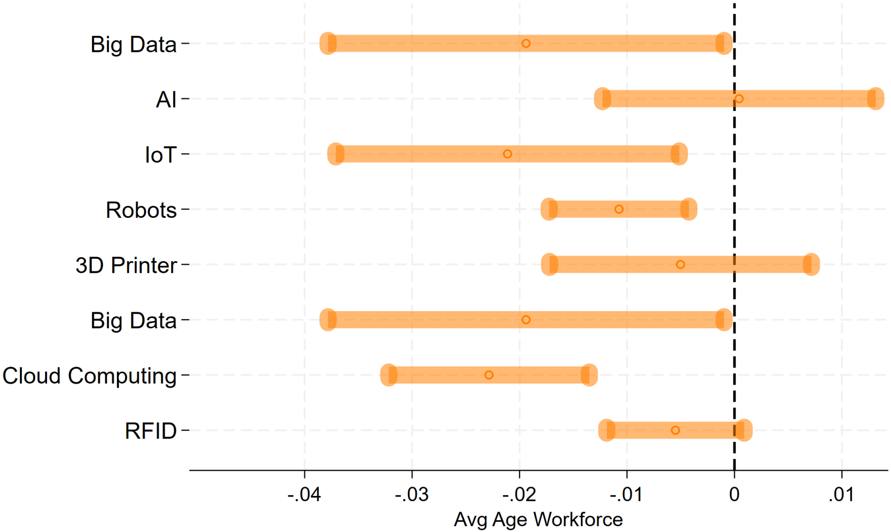
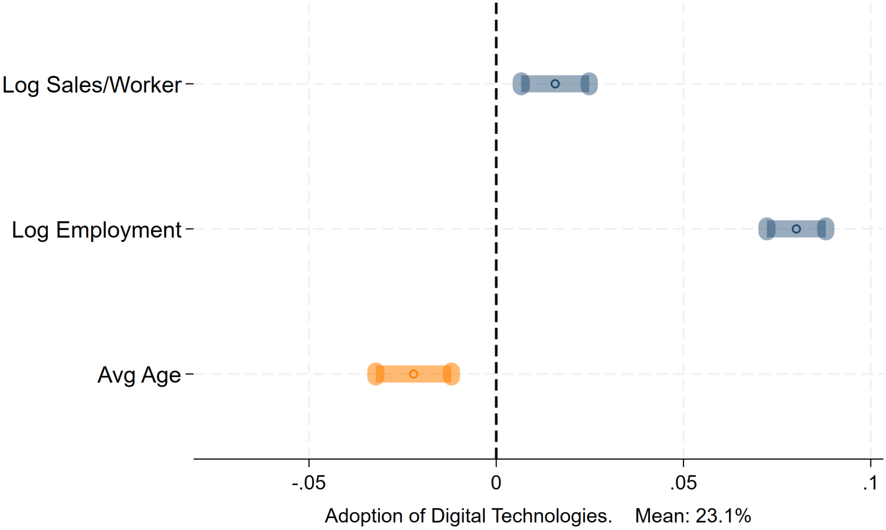
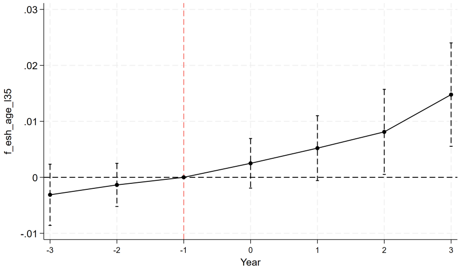
Adoption of Technologies in the Cross Section



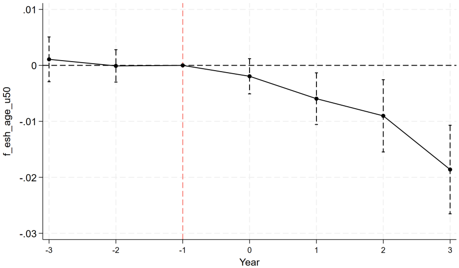
Adoption of Technologies in the Cross Section



Employment Share: Age Groups



(a) Young (< 35)



(b) Old (> 50)

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Employment: Age-Education Groups

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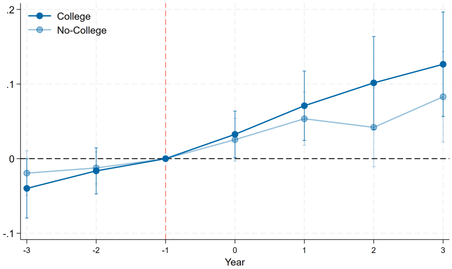
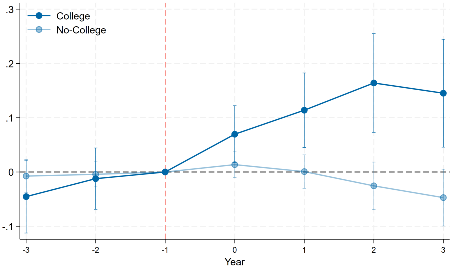
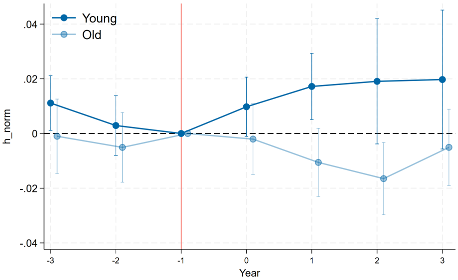


(a) Young

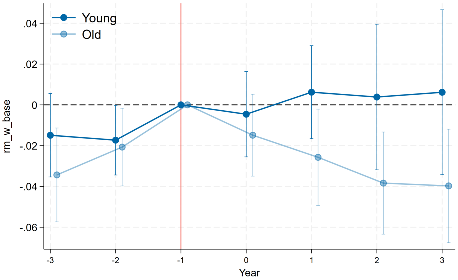


(b) Old

Incumbent Workers: Young vs Old



(a) Contractual Hours



(b) Salary

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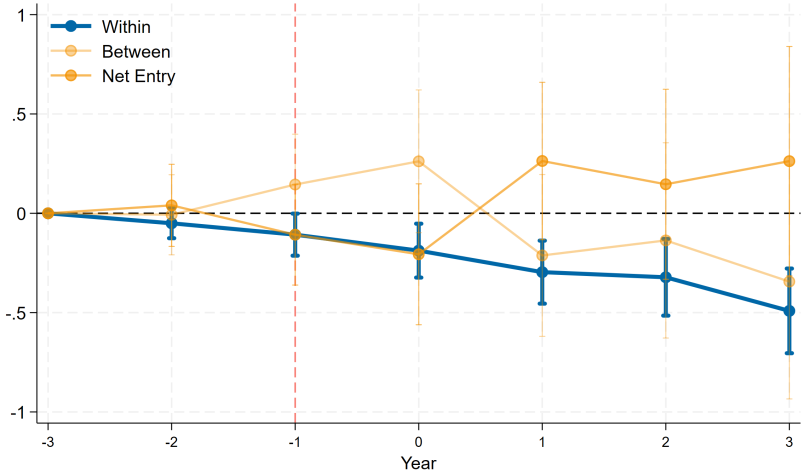
Avg Age: Occupation Decomposition

- y_{jt}: avg age of firm j in year t.
- $y_{j\hat{t}}$: avg age of firm j in reference year $\hat{t}$.
- Decomposition

$$y_{jt} - y_{j\hat{t}} = \underbrace{\sum_{o \in O^1_{jt}} \frac{s_{o,jt} + s_{o,j\hat{t}}}{2} (y_{o,jt} - y_{o,j\hat{t}})}_{\text{Within Component}} + \underbrace{\sum_{o \in O^1_{jt}} \frac{y_{o,jt} + y_{o,j\hat{t}}}{2} (s_{o,jt} - s_{o,j\hat{t}})}_{\text{Between Component}}$$

$$+ \underbrace{\sum_{o \in O^2_{jt}} s_{o,jt} y_{o,jt} - \sum_{o \in O^3_{jt}} s_{o,j\hat{t}} y_{o,j\hat{t}}}_{\text{Net Entry}}$$

Avg Age: Occupation Decomposition



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